TECHNICAL ANALYSIS AND CURRENT PERSPECTIVES FOR A BUTYRIC ACID PRODUCTION PLANT FROM SOYBEAN HULLS

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ABSTRACT

The replacement of petrochemical derivatives has become a global trend in recent years, driven by the increasing demand for sustainable alternatives for energy and material production. In this context, soybean hulls, a major by-product of the agricultural sector in Brazil, stand out as a source of fermentable carbohydrates that can be used to produce various valuable products, such as butyric acid, an important platform chemical with numerous applications in the food, energy, and pharmaceutical industries. Therefore, this work conducted a technical analysis of a potential industrial plant configuration for producing butyric acid from soybean hulls through fermentation using *Clostridium tyrobutyricum*. A process flow diagram and a mass balance of the process were developed. The process was divided into five main stages: biomass preparation, biomass pretreatment, enzymatic hydrolysis, fermentation, and purification. The study addressed the analysis and configuration of the plant for processing 5,000 kg of raw material in 5-day batches, yielding 6,030.26 kg of 11.4% butyric acid aqueous solution. The main limitations in the process are the high utility consumption and elevated enzyme costs. Thus, minimizing dilution in each stage and maximizing fermentation yields could be the best strategies to increase the feasibility of the plant.

Keywords: Biorefinery. Biomass Valorization. Renewable Chemicals. Fermentation. Enzymatic Hydrolysis.

1 INTRODUCTION

The increasing demand for sustainable and renewable chemical products has driven the research and development of alternatives to petroleum derivatives [1]. In this context, butyric acid has grown in the global market as an important platform chemical, notable for its various applications in the chemical, pharmaceutical, food, and cosmetic industries, as well as a precursor to biofuels [2].

Traditionally, the production of butyric acid is based on fossil sources; however, the pursuit of more sustainable processes has led to the development of new technologies, such as the microbiological route, which utilizes biomass in an anaerobic fermentation process to produce butyric acid instead of petroleum derivatives [2,3].

Among the various types of lignocellulosic biomass that can be used as substrates to produce butyric acid through microbial fermentation, soybean hulls stand out due to their high content of fermentable sugars, representing about 5-8% of the whole soybean seed [4]. Additionally, this agro-industrial by-product is abundant in Brazil, the world's largest soybean producer, with a production of 154.61 million tons in the 2022/2023 harvest [5].

In this context, this work aimed to propose and analyze the technical feasibility of an industrial plant for producing butyric acid from soybean hulls. The technical analysis addressed the main stages of the production process, including raw material preparation, pre-treatment, fermentation, and purification, and conducted a preliminary plant sizing, highlighting the benefits and challenges associated with the process. This analysis seeks to provide a solid basis for decision-making that contributes to the transition towards a more sustainable chemical industry.

2 MATERIAL & METHODS

The methodology adopted in this study was based on a literature review on the configuration, sizing, and operation of lignocellulosic biomass biorefineries [3,6,7] to choose the production model and plant configuration for butyric acid production. Additionally, existing literature on butyric acid production by fermentation was reviewed to obtain empirical data for performing the mass balance and sizing [8,9,10]. Based on this review, the plant was divided into the following units: Biomass Preparation, Pre-treatment, Enzymatic Hydrolysis, Fermentation, and Purification.

A calculation basis of 5000 kg of biomass (soybean hulls) being processed per batch for butyric acid production was assumed. The time required for the batch process was defined by the unit operations and plant operation obtained in the study development. The sizing of the units, equipment specification, and material balance calculations were performed based on the methodology described by Towler [11].

3 RESULTS & DISCUSSION

The process flow diagram in Figure 1 represents the configuration of the proposed butyric acid plant divided into its subunits, from the reception of raw materials to the final product. The figure presents the main process conditions and equipment of the plant.

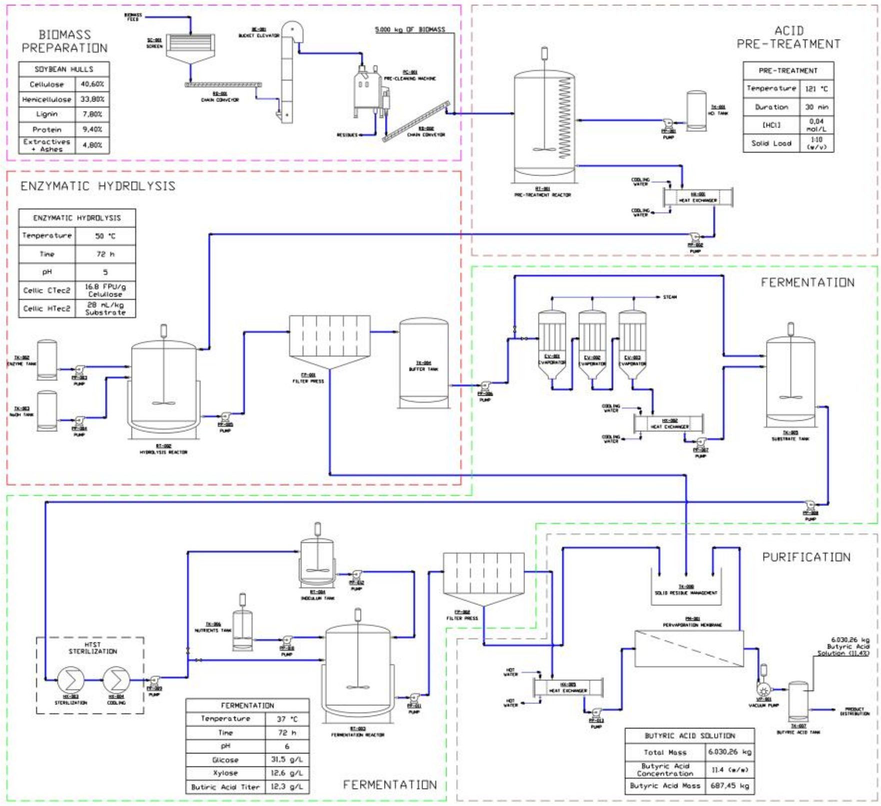

Figure 1 Process Flow Diagram of the Proposed Entire Butyric Acid Plant.

Mass Balance and Batch Process: During the batch processing of soybean hulls, 5000 kg of biomass are converted into reducing sugars through acid pretreatment and enzymatic hydrolysis. These sugars are fermented by the microorganism *Clostridium tyrobutyricum* and purified by pervaporation, yielding 6030.26 kg of product, an aqueous solution of butyric acid concentrated at 11.4% (w/w).

This batch process has a total duration of 171.3 hours, approximately 7 days of continuous operation. After the plant startup, some operations can be carried out in parallel, with fermentation and enzymatic hydrolysis occurring simultaneously. This reduces the total operation time to 89.5 hours or approximately 3.7 days. Considering the cleaning-in-place (CIP) process and maintenance, an average operation time of 5 days per batch can be considered after the initial startup.

Description of the Units:

Biomass Preparation: The butyric acid plant should be located near soybean processing industries to facilitate the supply of hulls, which are transported by tipping bulk trucks to the cleaning process. From there, the soybean hulls are sent to the pretreatment reactor, starting the process with 5000 kg of biomass.

Pretreatment: In the pretreatment, the biomass is diluted (1:10 w/w) and hydrolyzed with 0.04 mol/L hydrochloric acid at 121°C [8]. This process aims at the depolymerization of cellulose and hemicellulose, solubilization of lignin, and facilitation of the enzymatic hydrolysis process for the recovery of glucose and xylose [12]. Despite the high utility consumption due to dilution and the need for pH correction, dilute acid pretreatment is advantageous because of its high sugar conversion and relatively low inhibitor production. Other methods, such as steam explosion, have great potential for the pretreatment of soybean hulls, achieving high sugar conversion and reduced utility costs. However, the severe pressure and temperature conditions result in the formation of inhibitory compounds, such as furan and hydroxymethylfurfural, and low xylose conversion due to hemicellulose degradation [13,14], making dilute acid treatment preferable.

Enzymatic Hydrolysis: After the pretreatment, an enzymatic hydrolysis process occurs in which the enzymes Cellic CTec II and HTec II break down the long chains of cellulose into glucose and hydrolyze the remaining hemicellulose fraction into xylose [15]. This process takes place at pH 5.0 and 50°C for 72 hours in an agitated tank with a rotation speed of 150 rpm [8,15]. The use of the Cellic CTec II and HTec II cocktail is superior to other enzymes such as Celluclast [16].

Although the microorganism *Clostridium tyrobutyricum* favors the consumption of glucose as a substrate, the combined use of xylose results in a higher yield of butyric acid during fermentation [9]. Therefore, it is important to use HTec II for the conversion of hemicellulose to xylose. After this stage, the hydrolyzed broth is filtered to separate the liquid fraction rich in sugars from the insoluble solids, such as lignin, cell material, and others.

The filtered liquid fraction (rich in glucose and xylose) is then subjected to a concentration step by evaporation, so that the total sugar concentration in the fermentation is adequate. This step is also responsible for removing furfural, which is evaporated from the liquid fraction, although the concentration of other inhibitory compounds such as HMF may be slightly increased [7]. This stage represents one of the plant's highest energy demands, a consequence of the high dilution in the pretreatment process.

Fermentation: The concentrated sugar solution is sent to an anaerobic fermentation reactor, alongside the inoculum and salts that provide necessary nutrients for the conversion of substrate into butyric acid [8,9,10]. After dilution, the fermentation tank has initial substrate concentrations of 31.5 g/L and 12.6 g/L of glucose and xylose, respectively.

During fermentation, the microorganisms *Clostridium tyrobutyricum* consume the substrate to form butyric acid. This process occurs at 37 °C in an anaerobic environment with agitation at 100 rpm for 72 hours [8]. After the fermentation process and the consumption of the substrate by the microorganisms, a final concentration of 12.33 g/L of butyric acid is obtained in the tank, representing a conversion of about 30% of the substrate mass [8]. The total mass of butyric acid obtained is 687.44 kg. After fermentation, the fermented broth is sent to a filter, where the liquid fraction is separated. The solid fraction mainly contains microbial load and other insoluble solids from the fermentation.

Purification: The fermentation broth is purified through pervaporation, a membrane technique that selectively separates components based on their differences in solubility and diffusivity [17]. The use of pervaporation membranes offers advantages due to good energy efficiency, low utility consumption, and sustainability [18]. At the end of the process, butyric acid concentrated at 11.4% (w/w) is obtained in an aqueous solution with a total mass of 6030.26 kg.

Challenges and Optimization Strategies: Despite the growing interest in butyric acid production from biomass, the conventional fermentation process is not yet economically competitive due to its relatively low conversion rate and elevated production costs. Minimizing the utility consumption of the plant is one of the key challenges. Pretreatment methods that require less utility consumption, such as steam explosion, could enhance the feasibility of the process if the formation of inhibitory compounds were minimized. Studies using milder steam explosion conditions could make this possible. Additionally, enzymatic processes require a large amount of enzymes and a long hydrolysis period; therefore, optimizing this stage is one of the crucial factors for making a butyric acid plant viable. Other technologies that could be evaluated for process optimization include fed-batch processes, immobilized cells, and genetic modification of the microorganism to increase its tolerance to inhibitory compounds.

4 CONCLUSION

This study established the configuration and material balance basis for a butyric acid production plant from soybean hulls using batch fermentation, highlighting the process conditions and main aspects of each stage. Among the processing stages, pretreatment and enzymatic hydrolysis are critical phases that must be optimized to maximize sugar recovery, avoid the formation of inhibitory compounds, and reduce utility consumption in the plant. Nevertheless, the production of butyric acid from biomass has high potential. The market expansion, along with the trend of transitioning from petrochemicals to biorefineries and the development of new technologies, indicates that the process may become feasible in the future. Although more data and demonstration of the process at a pilot scale are needed, the technical analysis of the plant allowed for the comparison of different existing technologies and the determination of possible paths for the implementation of an industrial butyric acid plant, contributing to the development of a more sustainable chemical industry.

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